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Study of Effects of Channel Stabilization and Navigation Project on Missouri River Levels — Computed Hydraulic Characteristics of Missouri River Reaches before and after Stabilization

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The Corps of Engineers Missouri River Basin sediment series program was established for the development of practical sediment engineering for rational evaluation, regulation, and utilization of fluvial sediment phenomena. It was implemented as a comprehensive, basin-wide program for coordination of studies of sediment problems in the overall basin program for flood control and allied purposes as well as for continuity and perspective in the planning and design of individual projects. The program includes both investigations for the development of sediment transport theory and observations of existent and occurring phenomena for the purpose of developing the applications of theory to practical problems, developing empirical relationships and providing aids to judgment.

1. Method of Approach. The question as to how much the channel stabilization project has affected Missouri River stages obviously could be resolved most directly by comparing the measured rating curves established before the project with those established after its completion. This approach unfortunately cannot be taken since discharge measurements were not started on a routine basis in the Omaha District until 1929, and the period of record before the project is too short for a firm average rating curve to have been established. It remains then to use some principles of alluvial river hydraulics to compute the rating curve. The approach will be to analyze data from a number of Missouri River reaches in order to establish a general relationship among individual hydraulic elements such as cross section, slope, bed material, roughness, and discharge. The resulting general relationship will then be used to synthesize the discharge rating curve for a particular reach in which the cross section, slope, and bed material are known. Rating curves will be obtained analytically for conditions in a reach both before and after channel stabilization in order that there will be a common base for comparison. This analysis will be limited to bank-full stage and below because the overbank surveys are inadequate for computation of the overbank flow.

2. Equations. Discharge will be computed from the Manning equation

(1) $$Q = \frac{1.486}{n} AR^{2/3}S^{1/2}$$

where Q is the discharge (cfs), n is a variable coefficient expressive of the total resistance to flow and which also adjusts for any discrepancy between Equation 1 and the true relationship for the discharge, A is the cross section area (ft^2), R is the hydraulic radius (ft), and S is the energy slope which can be assumed equal to the water surface slope in tranquil streams such as the Missouri. A relationship* between the velocity and the size of sediment in the stream bed is

(2) $$V = \sqrt{12\ SR'g}\ (R'/k_s)^{1/10}$$

where V is the average velocity in the cross section (ft/sec), R' is a theoretical hydraulic radius which pertains to that portion of the boundary resistance attributed to the sand grains alone (ft), and k_s is the equivalent roughness diameter of the sand bed (ft). In alluvial beds k_s is taken as D_{65}, the sand grain diameter which is larger than 65% of the bed material by weight. After solving Equation 2 for R' we can compute

(3) $$n' = \frac{1.486}{V} (R')^{2/3}\ S^{1/2}$$

where n' is a Manning coefficient expressive of the sand grain roughness alone. The coefficient n' in Equation 3 is always smaller than n in Equation 1 which is an over-all coefficient integrating the resistance effects not only of the sand grains but also of bars, channel irregularities, meandering within the channel at low flows, vegetation, channel stabilization structures, and any other resistance elements. It seems reasonable that the incidence of sand bars and certain other irregularities on a moving bed must be related to the transport of the bed sediment. Many investigators (2, 3, 4, 5) have arrived at a relationship that can be put into the form

$$(4) \quad 1/\psi' \; \frac{R'S}{1.68D_{35}}$$

*Equation 2 is an approximation to Keulegan's (1) formula for flow over a granular boundary

$$V = 5.75 \sqrt{SR'g} \;\; \log_{10}(12.27 \frac{R'x}{k_s})$$

in the range $100 < R'/k_s < 100{,}000$ in which the Missouri River falls at all discharges. The two formulae are compared in Figure 1. The exponential approximation to the logarithmic form of the equation was adopted to simplify algebraic manipulations.

where $1/\psi'$ is a dimensionless parameter expressive of the capacity for transporting bed sediment as bed load per unit width of channel, the constant 1.68 is the specific gravity of ordinary sand submerged in water, and D_{35} is the grain diameter which is larger than 35% of the bed sediment by weight (ft). As $1/\psi'$ increases the rate of bed load transport increases, but not necessarily proportionally. The significance of the parameter $1/\psi'$ is discussed further in Appendix II.

3. The use of Reaches. In this study, average cross sections, slopes, and bed sediment analyses over reaches of the Missouri River are used. The rating curves derived therefrom are typical of average conditions in the reach and do not necessarily apply to local conditions near any one individual cross section. The method of computing the average section is described in Appendix I.

4. Roughness in Uncontrolled Reaches. In Equation 1, A, R, and S are geometrical elements which can be obtained by surveying cross sections and water surface profiles. n, however, is a variable depending on the friction of the sandy bed surface, the incidence of sand bars and other irregularities on the moving bed, meandering within the channel at low flows, and also vegetation and stabilization structures in the channel if these are present. In uncontrolled reaches of the Missouri where neither structures nor appreciable channel vegetation are present, it is reasoned (6,7) that the resistance of the remaining elements listed above can be expressed as a function of the bed material size and of the sediment transporting capacity. Using data from 8 uncontrolled Missouri River reaches from Williston, South Dakota to Rulo, Nebraska, in the period 1923 to 1952, the values of $1/\psi'$ and n/n' have been computed and plotted in Figure 2. Details of the computation are given in Appendix I. Table 1 contains a summary of the data on which Figure 2 is based. A single trend is clearly defined in Figure 2, indicating a general relationship for roughness in uncontrolled reaches. The use of Figure 2, in computing discharges at various stages in a particular reach is outlined in Appendix I. The Blair to Omaha reach in 1950 and 1952 is included among the uncontrolled reaches because the stabilization project has so greatly deteriorated in this location.

5. Roughness in Controlled Reaches. Using data from 6 controlled reaches in which stabilization projects have been completed, values of $1\psi'$ and n/n' were computed and plotted in Figure 3. Table 2 contains a summary of the data on which Figure 3 is based. All the points in Figure 3 fall above the average trend line of Figure 2, clearly indicating that controlled reaches offer more resistance to the flow than uncontrolled reaches except, perhaps, at low discharges. For values of $1/\psi'$ lower than 0.1, the trend of the points from controlled reaches seems to fall into that for the uncontrolled reaches. This is reasonable because at low discharges, which correspond to low values of $1/\psi'$, the water level is well down in the cross section and is free to act as though the stabilization structures were not there at all. The trend of the points in Figure 3 is not well defined, particularly for high values of $1/\psi'$. This is to be expected since the resistance in controlled reaches is not only a function of the bed load transport capacity but is also most likely a function of the degree of contraction of the natural river width, the departure from the natural river alignment, and the geometry of the stabilization structures. More data is needed to separate the effects of these variables. For use in the computations described below, the dashed line in Figure 3 was drawn by eye to approximate the best fit of the available points.

6. The Reaches Studied. For comparison of channel rating curves before and after the stabilization project in the Omaha District, two reaches have been chosen. One is the 20-mile reach immediately above Nebraska City; the other is the 25-mile reach downstream of Nebraska City to Rulo. The major portion of the channel stabilization project in both reaches was constructed between 1933 and 1937. Hydrographic surveys having been made in the years 1923, 1931, 1943, 1944, and 1952, the 1923 and 1952 surveys were chosen for the comparative study. Only the analysis of the reach above Nebraska City will be presented at this time. Analysis of the downstream reach is under way and will be presented later.

7. Analysis of Reach above Nebraska City. The water surface slope, the mechanical analysis of the bed material, and the average section are needed to compute a rating curve, making use of either Figure 2 or Figure 3. Water surface slopes measured during the hydrographic surveys of 1923, 1931, 1943, 1944, and 1952 indicate an average slope of 1.25 feet per mile. This reach is immediately downstream of the mouth of the Platte River 27 miles upstream of Nebraska City. The coarser sediment contributed by the Platte has caused the Missouri to aggrade and increase its slope immediately below the confluence in order to have the capacity to distribute the contributary sediment load on downstream. For this reason the slope in the 20-mile reach above Nebraska City is steeper than the average of about 0.8 feet per mile from Sioux City to Rulo. Although individual slope determinations vary about 5% from the average, no significant difference between 1923 and 1952 conditions is apparent from the available data; and the value 1.25 feet per mile is used for both conditions.

8. An average mechanical analysis curve based on about 40 bed samples obtained in this reach in 1952 indicates that D_{65} and D_{35} are 0.20 mm and 0.16 mm, respectively. Since no other data are available, it is assumed that the bed composition in 1923 was the same. This is considered a reasonable assumption because, on a long-time basis, the sand load supplied to the reach in 1952 must have been of about the same composition as in 1923.

9. Figure 4 compares the average sections computed from the 1923 and 1952 hydrographic surveys. The average sections could not be extended appreciably above average bankful stage 4.2 because the hydrographic data were limited to the channel and the adjacent banks. It will be noted that the 1952 section is divided into an "alluvial" portion and a "nonalluvial" portion. The "alluvial" portion lies riverward of the channel stabilization structures. Here the normal alluvial processes are free to occur, sediment movement is unobstructed, and the river is free to shape its own bed and to meander at very low flows. The "nonalluvial" portion lies between the riverward ends of the structures and the overbank. Normal alluvial processes are prevented in this area characterized by pile dikes normal to the flow, slack water, deposition induced by the structures, and vegetation on the deposits. The roughness is naturally high, and little flow occurs except at high stages. The line of demarcation between the nonalluvial channel and the overbank is not clear-cut; these areas behind the structures continue to be built up by deposition until they eventually become part of the overbank. The alluvial channel width in 1952, taken as the average clear width riverward of the structures, was found to be 860 feet in the reach above Nebraska City. This compares with 3,280 feet in 1923, taken as the average width between the first high banks.

10. Rating curves for 1923 and 1952 were computed by the method outlined in Appendix I and are compared in Figure 5. Figure 2 was used in evaluating the roughness for 1923, while Figure 3 was used in conjunction with the 1952 computations. It will be noted in Figure 4 that the alluvial channel in 1923 was 2,420 feet wider than in 1952. In order that the rating curve comparison might be based on equal widths of flow, the total channel discharge in 1952 was taken as the alluvial channel discharge plus the flow in the first 2,420 feet of nonalluvial channel. The Manning equation with a roughness coefficient of 0.06 was used in computing the discharge in the nonalluvial portion of the channel. The choice of the coefficient is not critical because, as Figure 5 indicates, the additional flow in the nonalluvial channel is less than 4% of the total at bankfull stage.

11. <u>Discussion of Results for Reach above Nebraska City</u>. It is well to remember that these results are for one reach only and that any definite conclusions should be reserved until the analyses of other reaches are available. The accuracy of the absolute values of discharge and stages computed herein is naturally open to question; but the real value of the study lies not in providing <u>absolute</u> answers for any one condition but in affording a means of <u>relative</u> comparison between 1923 and 1952 conditions.

It is not only possible to compare discharges as in Figure 5, but also, as in Figure 6, to study the relative effects of other hydraulic factors, changes in which combined to alter the channel rating curves after construction of the stabilization project. The question as to the capacity of the controlled versus the uncontrolled channel is partially resolved in Figure 5 which indicates that for discharges lower than about 50,000 cfs, the 1952 controlled channel has more capacity, having a lower stage for a given discharge. On the other hand, at higher discharges the controlled river has the smaller capacity, having 35% less discharge at bankfull stage. The average sections compared in Figure 4 indicate that, although 1952 section has been narrowed down considerably by the structures, the channel has so changed in shape that at low stages the width is greater than in 1923. This helps explain the greater capacity in 1952 for low stages. It is interesting to compare further the geometrical properties of the two channels with the help of Figure 4, 6b and 6d. Referring to Equation 1, it is seen that the factor $AR^{2/3}$ is the proper parameter by which channels should be compared on a geometrical basis, rather than by the width or the cross section area. At bankfull stage the geometry parameter $AR^{2/3}$ of the alluvial channel in 1952 is only 16% less than in 1923. This is true even though the width is 74% less and the cross section area is 46% less. It is evident that even though the stabilized 1952 section was much smaller, its shape became much more efficient; and, if the roughness had remained the same, it would have had only slightly less capacity at bankfull stage than in 1923. The geometry parameter $AR^{2/3}$ accounts for only 16% of the total 35% difference in the discharges at bankfull stage. An increase in the roughness accounts for the balance of the difference. Manning's "n" values of the 1923 and the 1952 channels are compared in Figure 6a. At intermediate and high channel stages the 1952 channel is substantially rougher than in 1923, which is the expected result of using Figure 3 in computing the 1952 rating curve. Training dikes protruding into the flow undoubtedly are one principal reason for this increase in roughness, but it is believed that a second and perhaps more important reason is the restriction on the freedom of the river to change its width and alignment. There is no reliable data to bear this out as yet, but it is believed that the river will follow the path of least resistance if it is free to adjust slightly its width and alignment for each discharge. As a matter of interest, the average velocity and the bed load transporting capacity per unit width in the two channels are compared in Figure 6c. Both velocity and transport capacity are greater for all stages in 1952. The plotting of the parameter $1/\psi'$ in Figure 6c is intended only as an indication of relative capacities per unit width and is intended to convey no quantitative information. It is reasonable to expect the transporting capacity per unit width to be greater in 1952. On the average, the bed sediment supply to the reach must be the same in 1952 as in 1923. Since the 1952 channel does not appear to be aggrading, and is in fact deeper than in 1923, this reach must be continuing to transport the bed sediment supplied to it. In order to maintain the same transport rate in a greatly reduced width of channel, the transporting capacity per unit width would have to increase.

12. Conclusions.

a. Figure 2 can be used with considerable confidence in estimating the roughness in uncontrolled reaches on the Missouri River.

b. The controlled reaches on the Missouri River are definitely rougher than the uncontrolled reaches for intermediate and high discharges within the channel.

c. More data are required before the roughness of controlled Missouri River reaches can be predicted with confidence.

d. In the reach above Nebraska City, the capacity of the 1952 channel exceeds that of the 1923 channel at discharges less than 50,000 cfs.

e. In the reach above Nebraska City, the bankfull capacity of the 1952 channel is 35% less than in 1923.

f. The 1952 section above Nebraska City has a far more efficient hydraulic shape than in 1923; the loss in bankfull capacity can be attributed somewhat to the much smaller 1952 channel size and to a greater extent to an increase in roughness.

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